

EVIDENCE FOR INTRINSIC MAGNETIC MOMENTS IN BLACK HOLE CANDIDATES

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Draft version February 1, 2008

ABSTRACT

We present evidence that the power law part of the quiescent x-ray emissions of neutron stars in low mass x-ray binaries is magnetospheric in origin. It can be very accurately calculated from known rates of spin and magnetic moments obtained from the $\sim 10^{3-4}$ times brighter luminosity at the hard spectral state transition. This strongly suggests that the spectral state transition to the low hard state for neutron stars is a magnetospheric propeller effect. We test the hypothesis that the similar spectral state switches and quiescent power law emissions of the black hole candidates might be magnetospheric effects. In the process we derive proposed magnetic moments and rates of spin for them and accurately predict their quiescent luminosities. This constitutes an observational test for the physical realization of event horizons and suggests that they may not be formed during the gravitational collapse of ordinary matter.

Subject headings: black hole physics — X-ray: stars – binaries: close – stars: neutron – stars: individual (GRS 1124-68, A0620-00, XTE J1550-1564, GS 2000+25, GRO J1655-40, and GS 2023+338)

1. INTRODUCTION

It has recently been claimed that the very low, but nonzero, quiescent luminosity levels of galactic black hole candidates (GBHC) in low mass x-ray binary systems (LMXB) constitutes evidence of event horizons (Garcia et al. 2001). This interpretation of the observations relies on an advection dominated accretion flow (ADAF) model (Narayan, Garcia & McClintock 1997) in which the energy released by accretion is stored as heat in a radiatively inefficient flow which eventually disappears through an event horizon. Garcia et al. (2001) state their belief that any straightforward explanation of the differences of quiescent luminosities of GBHC and neutron star (NS) systems, whether based on ADAFs or not, will require postulating an event horizon in GBHC. In this work we will show that their quiescent luminosities may have a rather mundane explanation as magnetospheric emissions.

This surprising assessment arises from the strong broad band similarities of NS and GBHC, particularly in quiescence (e.g., Tanaka & Shibazaki 1996, van der Klis 1994). These similarities include power law emissions of both NS and GBHC. Photon indexes of ~ 2 are found in both types of object, extending into quiescence. As shown below, spins of a few hundred Hz, combined with magnetic moments of a few 10^{27} G cm³ lead to magnetospheric power law emissions of 10^{32-33} erg/s for NS. This spin-down luminosity is as inevitable in the magnetic NS of LMXB as it is in ordinary pulsars. But given the similarities with GBHC, this significantly sharpens the question of how the latter produce their quiescent emissions. It will be made clear that spins of a few tens of Hz and magnetic moments of order 10^{29} G cm³ would produce their quiescent luminosities of 10^{30-32} erg/s. Although the existence of objects compact enough to qualify as black hole candidates is beyond question and the existence of black holes is accepted by most astrophysicists, it is still observationally

unclear whether event horizons can be physically realized in the collapse of stellar mass objects. Hence it is still necessary that we be able to exclude the possibility that GBHC might be intrinsically magnetized objects before we can say that they truly are black holes. It has recently been suggested (Mittra 2000) that, within the framework of General Relativity, trapped surfaces cannot be formed by collapse of physical matter and radiation. Such a view was also held by Einstein (1939).

In this paper, we observationally test whether event horizons are necessary for the explanation of the low quiescent x-ray luminosities of GBHC. Using only the most rudimentary generic features of strong-field gravity, we consider a model of GBHC with intrinsic magnetic moments. We assume the magnetic fields to be intrinsic because we require them to be anchored and co-rotating with the central object. We find that they also need to be stronger than those that can be generated via disk dynamos (Livio, Ogilvie & Pringle 1999) and more persistent than can be expected with intense accretion onto charged Kerr-Newman black holes (Punsly 1998). Field strengths of magnitude similar to those we consider have been implied by the kinetic power of the jets and synchrotron emissions of the GBHC, GRS 1915+105 (Gliozzi, Bodo & Ghisellini 1999, Vadawale, Rao & Chakrabarti 2001). We assume that the magnetic field mediates the spectral state switches of NS and also drives the power law part of the quiescent emissions. We find that the magnetospheric model accords with many other observed features.

Even the weakly magnetic ($\sim 10^8$ G) atoll class NS produce significant magnetic stresses on accreting plasma. At the co-rotation radius (where the Keplerian orbit frequency matches the magnetosphere spin rate) the magnetic pressure is $\sim 10^7$ bar. When the inner radius of the accretion disk expands beyond the co-rotation radius, the magnetosphere acts as a propeller, cutting off the flow to

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the NS surface. This causes a spectral state transition as surface impacts and soft surface thermal emissions abate (Campana et al. 1998, Zhang, Yu & Zhang, 1998, Cui 1997, Stella, White & Rosner 1986). The magnetic propeller effect has been invoked (Menou et al. 1999) to explain how an ADAF might be prevented from reaching the surface of a quiescent NS and producing high NS luminosity. It is widely believed that ADAFs for NS are stopped by the propeller effect, otherwise a typical, optically implied, ADAF mass flow rate of 5×10^{15} g/s would produce a very non-quiescent luminosity of $\sim 7 \times 10^{35}$ erg/s upon reaching the surface of a NS. But such a flow rate would at least reach the light cylinder radius of ~ 100 km for an atoll spinning at 500 Hz. If reversed there, it should then radiate $\sim 5 \times 10^{34}$ erg/s, which is between one and two orders of magnitude larger than the observed quiescent luminosities of NS. Bisnovatyi-Kogan and Lovelace (2000) also find that electron heating of an ADAF plasma may lead to luminosities about 25% as large as those of a conventional thin disk with the same accretion rate, which is far beyond quiescent NS luminosity. These quantitative difficulties with the ADAF model, the similar spectral state switches of GBHC, and the need to test the claimed detection of event horizons have provided the motivation for considering a magnetospheric alternative.

2. ANALYSIS

Quiescent x-ray emissions of NS show soft surface thermal and power law components of roughly the same luminosity (Campana et al. 2000, Rutledge et al. 2001). The magnetospherically driven power law emissions that we consider here would be the minimum quiescent luminosities for NS. As we are not accounting for surface thermal emissions, factor of two disagreements between measured and calculated quiescent luminosities would be acceptable; indeed even larger variances could occur as a result of the stochastic nature of the magnetospheric emissions. As this is being written, no soft thermal emissions have been reported for quiescent GBHC. Garcia et al. (2001) report that their quiescent emissions are consistent with single power laws with photon index ~ 2 , similar to those of NS. We shall assume that the power law emissions are magnetospheric for both NS and GBHC. These emissions can be calculated as magnetospheric spin-down luminosities using Becker & Trümper's (1997) correlation of x-ray luminosity with rate of loss of rotational energy, $\dot{E} = 4\pi^2 I \nu \dot{\nu}$, where I is the moment of inertia of the star and ν its rate of spin. We assume that the energy loss derives from the magnetic torque on an axially aligned rotating magnetic dipole, which gives $\dot{E} = 32\pi^4 \mu^2 \nu^4 / 3c^3$, (Bhattacharya & Srinivasan 1995) where μ is the magnetic moment and c the speed of light. (Equating these energy loss rates and taking $I = 10^{45}$ g cm² provides the standard equation for determining magnetic moments from pulsar spin-down data $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G, with $P = \nu^{-1}$.) Becker & Trümper found the x-ray luminosity to be about $10^{-3} \times 4\pi^2 10^{45} \nu \dot{\nu}$ erg/s. Thus the quiescent x-ray luminosity would then be given by :

$$L_q = 10^{-3} \times 10^{45} \frac{32\pi^4 \mu^2 \nu^4}{3c^3 I} = (4.8 \times 10^{30} \text{ erg/s}) \frac{\mu_{27}^2 \nu_2^4}{m R_6^2} \quad (1)$$

Here we have taken the magnetic moment to be $\mu_{27} \times 10^{27}$ G cm³, the spin frequency to be $100 \times \nu_2$ Hz, the mass of the star as m in M_\odot , and the radius as $10^6 \times R_6$ cm.

We assume that accretion flow takes place in a geometrically thin, optically thick accretion disk. Except in quiescence, the inner disk radius is assumed to be the same as the magnetospheric radius, r_m . This radius is the location at which the magnetosphere is capable of the appropriate rate of removal of angular momentum from the inner disk. Mathematically, the result is similar to that obtained by equating the impact pressure of accreting plasma to the magnetic pressure. For spherically symmetric accretion (e.g. Campana et al. 1998, Equation 1):

$$r_m = K \left(\frac{\mu_{27}^4}{m \dot{m}_{15}^2} \right)^{1/7} \quad (2)$$

where \dot{m}_{15} is the mass accretion rate in units of 10^{15} g/s and K is a scale factor. For spherical accretion, $K = 233$ km, however, as noted by Campana et al. (1998), this needs to be corrected by a factor of ~ 3 to account for the difference between disk accretion and spherically symmetric accretion. For this reason, we will take $K = 80$ km. This brings the magnetospheric radii into close agreement with those of an elaborate model of a gas pressure dominated disk (Ghosh & Lamb 1992). (For the present purposes of calculating luminosities, the extent to which the disk is threaded by the magnetic field of the central object is unimportant because it does not directly have a large effect on the accretion energy released for a given inner disk radius.) $K = 80$ km, is a poorly known parameter and the calculations to follow are fairly sensitive to its value. Errors in K are reflected in errors of determination of μ_{27} and then in calculations of L_q .

The spectral state switch takes place when the disk inner radius matches the co-rotation radius, r_c . This can be expressed in terms of the Keplerian orbit frequency, which is also the spin rate of the star, as:

$$r_c = (70 \text{ km}) \left(\frac{m}{\nu_2^2} \right)^{1/3} \quad (3)$$

The light cylinder radius is given by $r_{lc} = (480 \text{ km})/\nu_2$. When the disk inner radius lies inside the light cylinder, we assume that the disk luminosity is given by

$$L = \frac{GM\dot{m}}{2r_m} \quad (4)$$

Here G is the Newtonian gravitational force law constant, and \dot{m} the accretion rate. This corresponds to conversion of half the accretion potential energy to luminosity via viscous dissipation. This cannot be entirely accurate as some energy extracted from the rotation of the central object drives the propeller outflow and may contribute to the luminosity. In addition, relativistic corrections are needed near the innermost marginally stable orbit, however, these are unimportant for radii as large as most co-rotation radii for the objects considered here. When all of the accreting matter actually strikes the star, we take the luminosity to be

$$L = \eta \dot{m} c^2 \quad (5)$$

where η is the efficiency of conversion of mass-energy to luminosity, which should be determined from models of gravitating objects in strong-field limits. For NS,

$\eta = GM/(c^2 R) \sim 0.14$ is both customary and adequate. For GBHC, η is a parameter to be determined from observational data. Three additional characteristic luminosity levels (Campana et al. 1998) are used here. L_{min} corresponds to the accretion disk having penetrated inside the co-rotation radius; enough to allow essentially all of the accreting matter to reach the central object. At this point spectral softening ends. L_c is the luminosity when the disk inner radius is only a little beyond the co-rotation radius, the propeller reverses the inflow and a hard spectrum is produced. $L_{q,max}$ is the luminosity with disk radius at the light cylinder. Using $r_c = r_m$ to eliminate \dot{m} and setting $r = r_c$ in Equations 4 and 5 there follows:

$$L_{min} = (1.4 \times 10^{36} \text{ erg/s}) \eta \mu_{27}^2 \nu_2^{7/3} m^{-5/3} \quad (6)$$

and with $r = r_c = r_m$

$$L_c = (1.5 \times 10^{34} \text{ erg/s}) \mu_{27}^2 \nu_2^3 m^{-1} \quad (7)$$

Similarly, using $r_m = r_{lc} = r$ yields

$$L_{q,max} = (2.6 \times 10^{30} \text{ erg/s}) \mu_{27}^2 \nu_2^{9/2} m^{1/2} \quad (8)$$

For NS we shall assume that $m = 1.4$, $R_6 = 1.5$ and $\eta = 0.14$ unless otherwise noted. For GBHC we have used literature values for mass.

As the magnetic moment, μ_{27} , enters each of Equations 1, 6, 7, 8, it can be eliminated from ratios of these luminosities, leaving relations involving only masses and spins. With mass values given, the ratios then yield the spins. Here we will use Equation 6 or 7 to find μ_{27} , after which Equation 1 yields L_q . Alternatively, if the spin is known from burst oscillations, pulses or spectral fit determinations of r_c , one only needs one measured luminosity to enable calculation of the remaining μ_{27} and L_q .

3. CALCULATIONS

Observational data and calculations leading to luminosities shown in Table 1 are detailed in the appendix.

Neutron Stars—

Sax J1808.4-3658 is the only NS LMXB to show x-ray pulses. Observed spins of five other NS were determined from burst oscillations (Strohmayer 2000). For Aql X-1, 4U 1608-52, and Sax J1808.4-3658, the values of spin and L_c or L_{min} were used to calculate the values of μ_{27} shown in Table 1. Spins and magnetic moments were then used to obtain their calculated quiescent luminosities. The agreement is very good, however the identification of L_{min} for Sax J1808.4-3658 is somewhat uncertain (see appendix). On the other hand, Sax J1808.4-3658 is a millisecond pulsar for which we can be reasonably certain that Equation 1 would yield its quiescent power-law luminosity. In this case, we can invert the process and use μ determined from Equation 1 to verify our choices of L_{min} and L_c .

An important step in this analysis consists of testing the validity of the use of luminosity ratios to determine both spins and magnetic moments. For the first two NS of Table 1, we have used the ratio L_{min}/L_c to determine spins shown as calculated values in the table. Both agree with observed values within 20%. We used these spins and observed L_c to re-evaluate μ_{27} and then recalculated values of $\log(L_q)$ of 32.5 and 33.5 for them. If small errors of

spin arise from the use of ratios and the values of L_{min} or L_c are not seriously in error, then compensating shifts of calculated magnetic moments seem to leave the calculated quiescent luminosities relatively unchanged.

As no burst oscillations have yet been reported for Cen X-4, we used the ratio $L_{min}/L_q = 4$ to obtain a spin of 430 Hz and magnetic moment $\mu_{27} = 1.1$. The calculated quiescent luminosity is 6×10^{32} erg/s ($\log(L_q) = 32.8$), compared to 2.5×10^{32} erg/s ($\log(L_q) = 32.4$) observed. The agreement between luminosities calculated via the ratio method and those observed for three NS is good, especially when one considers that the calculated values were based on information obtained from luminosities that were more than 10^3 larger. This strongly suggests that the spectral state switch for NS is a magnetospheric effect and that magnetospheric spin-down accounts for much of the quiescent luminosity.

Quiescent luminosities for 4U 1916-053, KS 1731-26 and 4U 1730-335 were determined using observed spins and values of L_c or L_{min} estimated at the endpoints of the spectral state transitions. Their calculated quiescent luminosities are included here as predicted values. We note that the magnetic moments that we find here are comparable to those found for millisecond pulsars with similar rates of spin.

Two entries have been included for Cir X-1. Observed luminosities have been corrected for a distance of 5.5 kpc rather than the 10 kpc originally reported (Dower, Bradt & Morgan 1982). This also brings its magnetic field ($B = \mu R^{-3}$) into agreement with a value of $\sim 4 \times 10^{10}$ G based (Iaria et al. 2001) on an accretion disk inner radius that was obtained from fitting spectral data. Cir X-1 is, in many respects, the NS that behaves most like a GBHC. It was thought to be a GBHC for a long time, until it displayed Type 1 bursts. It has been clearly identified as a Z source (Shirey, Bradt & Levine 1999). It seems to have a spin and magnetic moment more like those of the GBHCs shown further down in Table 1. The lower spin rate is commensurate with its ‘kHz’ QPOs, which have an onset around 20 Hz. The GBHC properties that Cir X-1 seems to possess may simply be due to a stronger magnetic field, but it seems plausible that it may also have the larger mass of a GBHC. If it has the larger mass, then as a burster it clearly has no event horizon. If not, then it demonstrates that the magnetic moments may be involved in the production of the high frequency QPO. It is of interest, that only its calculated magnetic moment changes significantly if we suppose it to have different mass. This is also the case for the GBHC.

Black Hole Candidates—

For the GBHC, we have three unknown parameters, μ_{27} , η , and R_6 to determine. We use estimates of the inner disk radius at co-rotation and Equation 3 to determine the spin frequencies. We use Equation 7 to obtain μ_{27} and then Equation 6 to evaluate η . For GRS 1124-68, GS 2023+338, XTE J1550-564 and GS2000+25, inner disk radii obtained from spectral fits (see appendix) are 400 km, 224 km, 228 km and 500 km, respectively. The corresponding values of ν_2 and μ_{27} are shown in Table 1. For the first three objects, for which reliable values of L_{min} have been found, the values of η were, 0.34, 0.48 and 0.49, respectively. For the remainder of this work we shall use $\eta = 0.4$ as our best guess. This choice was used for the second tabular entry

TABLE 1
CALCULATED AND OBSERVED QUIESCENT LUMINOSITIES

Object	m M _⊙	L_{min} 10 ³⁶ erg/s	L_c 10 ³⁶ erg/s	μ_{27} Gauss	ν_{27} cm ³	ν_{obs} Hz obs.	ν_{calc} Hz calc.	log (L_q) erg/s obs.	log (L_q) erg/s calc.
Aql X-1	1.4	1.2	0.4	0.47	549	658		32.6	32.5
4U 1608-52	1.4	10	2.9	1.0	619	534		33.3	33.4
Sax J1808.4-3658	1.4	^a 0.8	0.2	0.53	401	426		31.8-32.2	32
Cen X-4	1.4	4.4	1.1	1.1		430		32.4	32.8
4U 1916-053	1.4	~14	3.2	3.7	270	370			33.0
KS 1731-26	1.4		1.8	1.0	524				33.1
4U 1730-335	1.4	10		2.5	^b 307				32.9
Cir X-1	1.4	300	14	170		35			32.8
Cir X-1	7	300	14	420		33			32.6
GBHC									
GRS 1124-68	5	240	6.6	720		16		< 32.4	31.9
GS 2023+338	7	1000	48	470		46		33.7	33.2
XTE J1550-564	7	^c 90	4.1	150		45		^d 32.8	32.2
GS 2000+25	7		0.15	160		14		30.4	30.2
GRO J1655-40	7	31	1.0	250		19		31.3	31.2
A0620-00	4.9	4.5	0.14	50		26		30.5	30.4
Cygnus X-1	10		30	1260		23			32.7
GRS 1915+105	7		12	130		^e 67			32.8

^aCorrected to 2.5 kpc (in't Zand et al. 2000, Dotani et al. 2000), ^b(Fox, D. et al. 2000), ^cd = 4 kpc, ^d(Tomsick & Kaaret 2001) ^eGRS 1915+105 Q ≈ 20 QPO was stable for six months and a factor of five luminosity change.

Observed quiescent luminosities are from Garcia et al. (2001). Observed spins as reported by Strohmayer (2000). Other table entries are described in the text and appendix.

for Cir X-1. We note that this choice is consistent with interpreting the ‘ultrasoft’ radiations of the GBHC as red-shifted surface radiations. If z is the redshift, it is given by $z = \eta/(1 - \eta) = 0.7$, for $\eta = 0.4$. The surface thermal emissions would then be shifted to 1.7X lower than rest frame energies and they would appear unusually soft.

At this point, we must also estimate the radii of GBHC before we can calculate the quiescent luminosity. This choice must be consistent with our choice of η . In metric gravity theories, $\eta = 1 - \sqrt{g_{tt}}$, where g_{tt} is the time component of the spacetime metric. In standard Schwarzschild coordinates, $g_{tt} = (1 - 2GM/c^2R)$. For $\eta = 0.4$, the radius of a 7 M_⊙ object would be 32 km. In isotropic coordinates, however, $R = 21$ km would result. Since the applicability of either number is in question, we will take $R = 20$ km for use here. R enters here as part of the expression of rotational inertia for a GBHC. Quiescent luminosities are only moderately sensitive to the value used, but any choice for GBHC is clearly a guess.

Using $R_6 = 2.0$ in Equation 1, we calculate the quiescent luminosities of GRS 1124-68, GS 2023+338, XTE J1550-564 and GS 2000+25 shown in Table 1. We use the ratio method with $\eta = 0.4$ and $R_6 = 2$ to obtain quiescent luminosities for GRO J1655-40 and A0620-00. For the six for which comparisons can be made, the agreement with observed values is excellent. The remaining entries in the table, which lack observed values for comparison are to be understood as predictions. If we use the ratio method for XTE J1550-564 rather than the spectrum fit value for r_c , we would find $\log(L_q) = 32.1$ for $\eta = 0.4$. An esti-

mated co-rotation radius of 400 km was used to determine the spin for Cygnus X-1 (see appendix). We identify a QPO frequency of GRS 1915+105 as its spin frequency. We predict values of L_{min} to be 1.6×10^{38} erg/s for GRS 1915+105 and 6.4×10^{38} erg/s for Cyg X-1.

4. DISCUSSION

The luminosity at the arrest of decline in the light curves of Aql X-1 (Campana et al. 1998, Fig. 1) and Sax J1808.4-3658 (Gilfanov et al. 1998) near the end of an outburst is a factor of ~ 5 higher than the final quiescent luminosity. The luminosity at the arrest for Aql X-1, 1.2×10^{33} erg/s, agrees within 25% of $L_{q,max}$ calculated using Equation 8 and the spins and magnetic moments obtained from spectral state switches. Similar factors of 5 to 10 are found for GBHC. This indicates that during the decline to quiescence, the inner radius of the accretion disk continues to expand beyond the light cylinder. If the inner disk remains optically thick, as little as $\sim 10^{30}$ erg/s emanating from the central star would be capable of heating it to the instability point and/or ablating it if nearer than $\sim 10^5$ km. For NS, it seems clear that the quiescent inner disk must be essentially empty to this radius. Even if the flow in the inner disk is an ADAF, the flow rate would be so low that it could contribute little to the luminosity. It would also be most peculiar for the ADAF luminosity to depend, as we have shown, on the spin and magnetic moment of the NS. It is difficult to accept that high flow rate ADAFs exist for GBHC, but not for NS of similar orbital period. A more circumspect view is that the similar quiescent behaviors of

GBHC are due to similar magnetospheric causes.

The picture of LMXB that emerges from this work is that of magnetized central objects surrounded by accretion disks that have inner radii dictated either by stability considerations in quiescence or magnetic stresses at much higher luminosities. Only at very high accretion rates does the disk push in to the marginally stable orbit. Since many spectral and timing characteristics observed for GBHC and NS fit well within this broad picture, we will consider a few of them. These considerations have gained impetus from the recent discoveries of hard spectral tails for NS extending beyond 200 keV (e.g., Di Salvo et al. 2001). This removes one of the last of the qualitative spectral differences thought to differentiate NS and GBHC. This is not to say that there are no spectral differences of NS and GBHC. There are clear differences that can be attributed to greater mass for GBHC. For example, Eddington limits are higher and Keplerian frequencies at the marginally stable orbit would be much smaller for GBHC. Another major difference is that a prograde angular momentum at the ~ 500 Hz spins of NS in LMXB might cause the marginally stable orbit radius to be less than that of the star. Thus the boundary region at the inner disk could differ between most NS and GBHC, but there are no presently known differences that can be attributed to an event horizon.

Cyg X-1 is a persistent source that is usually found in a low, hard state, but occasionally enters a high, soft state with only a factor of 2 or 3 change of bolometric luminosity. With the inner disk radius at ~ 400 km in the hard state, the disk efficiency ($GM/2c^2r$) is 0.018, compared to the 0.4 efficiency for accretion to the surface. Hard disk and ultrasoft surface radiations can contribute equally to the luminosity if only 0.045 of the accreting matter actually crosses the co-rotation radius. Thus a spectral state change can occur for very little change of accretion rate and small change of overall luminosity. Here the propeller effect provides a clear and simple explanation of the mysterious spectral pivoting shown by many GBHC. Clearly one cannot take the ratio of luminosities here as an indicator of spin. Only if there is some broader measure of spectral hardness that can be measured over the entire interval from L_c to L_{min} can reliable results be obtained. Since a substantial increase of radiation pressure on the inner disk results from small change of accretion rate, it appears that Cyg X-1 usually stays relatively well balanced in a relatively low state. If the accretion rate is highly variable with the inner disk near co-rotation oscillations can result.

Pulsars such as V0332+53, atoll NS, and GBHC all exhibit flickering in low states. This has a natural explanation as Rayleigh-Taylor instability shot leakage across the magnetopause. The larger amplitude flickering for GBHC and pulsars with large magnetic moments is a result of infall from larger radii. Long time lags at low Fourier frequencies (Nowak et al. 1999) imply very slow propagation speeds ($< 0.01c$) for the luminous plasma disturbances. Such slow speeds are to be expected for plasma in a magnetosphere.

When well below the Eddington limit, GBHC are much like the atoll NS examined here. One of the reasons for this might be that the magnetic stresses at the co-rotation radius are of the same order, $\sim 10^7$ bar for both. Z class

NS have only slightly larger co-rotation radii than atolls, but have magnetic fields about 10X larger. The magnetic stresses at their co-rotation radii are much larger, $\sim 10^{8-9}$ bar. Accretion rates near the Eddington limit are needed to push the magnetopause inside the co-rotation radius. An optically thick boundary layer eventually blankets the magnetosphere and obscures the radiation from the star. In this way the luminosity can decline while the accretion rate actually increases, producing the familiar ‘Z’ track in the hardness vs. luminosity diagram. The track is also seen in color-color diagrams. Portions of such tracks are occasionally seen in GBHC such as GX 339-4 (Miyamoto et al. 1991) or GS 2023+338 (Życki, Done & Smith 1999a, 1999b). Typical normal branch oscillations $\sim 4-10$ Hz are observed for them. In addition to Z sources being infrequent bursters that have shown no burst oscillations, we have generally omitted Z sources in this work because the radiation pressure materially affects the inner disk in the spectral switch region and changes the manner in which radius scales with accretion rate.

A superluminal jet was produced by GRS 1915+105 contemporaneous with the oscillations described for it in the appendix. Chou & Tajima (1999) devised a promising model for such pulsed ejections in which a poloidal magnetic field of unspecified origin is toroidally wound by the inner disk until it becomes buoyantly unstable and is ejected from the inner disk. In their model, they artificially stopped the flow through the event horizon using a pressure of unspecified origin. It is widely believed that magnetic fields generated in the accretion disks of black holes can produce strong poloidal fields threading the event horizon. This seems unlikely, (Livio, Ogilvie & Pringle 1999, Punsly 1998) however, because the same field threads the disk where magnetic pressures can at most be comparable to the gas pressure. GBHC that possessed intrinsic magnetic moments could provide the necessary conditions for applicability of the Chou & Tajima model. In any event, disk generated magnetic fields cannot provide a propeller effect that cuts off the flow into the interior for long times. After the flow cuts off, the field would decay in about the light crossing time for the original region of field. The disk would then refill on a slower viscous time scale. It is also not obvious that cutting off the flow to an event horizon could produce a spectral state switch. Considering the high accretion rates involved in the jet production of GRS 1915+105, it seems unlikely that the inner charge ring of a charged, rapidly spinning Kerr-Newman black hole (Punsly 1998) could be the source of the strong magnetic field at the base of its jet.

In our analyses, we have generally used luminosities obtained in the declining phase of outbursts. During rising phases, there is a transition through an intermediate state, complete with onset of several QPO, when the co-rotation radius is traversed. There may be some hysteresis in luminosities of the spectral state transitions of rising and declining phases. This sometimes appears in temporal shifting of the position of Z tracks in hardness vs. luminosity diagrams. Substantial changes in luminosity for the tracks over weeks are relatively common. Such behavior may be due to screening of the magnetic fields by accumulations of accreted matter on the surface. If the field weakens, it would permit matter to go deeper into the gravitational

well and thus change the luminosity at which some phenomena such as QPO are observed.

The inner disk radius and the outer point of disengagement of disk and magnetosphere would be natural boundaries for the generation of QPO. Except near the co-rotation radius the disk material would be subjected to either braking or accelerating torques. These would produce a shear across the co-rotation region, depending on the extent of magnetic field threading of the disk. It would not be surprising to have oscillations generated by the shear. Most of the current models (beat frequency, relativistic precession and magnetospheric coriolis oscillators) of high frequency QPO rely on variations of the inner disk radius to generate the variation of at least one of the high frequency QPO seen in LMXB. Recent simulations (Kato et al. 2001) have shown that another high frequency QPO is generated by reconnection of magnetic field lines at the inner disk radius. The field lines are toroidally wound by the inner disk until they break. For both NS and GBHC, the high frequency QPO begin near the spin frequency and increase to values nearly commensurate with that of the marginally stable orbit. The onset near the spin frequency is consistent with our interpretation of mass beginning to reach the central object when the corotation radius is traversed. This consistency adds confidence to our use of disk co-rotation radii determined from spectral fitting as these co-rotation radii have provided some of our spins.

The hypothesis that GBHC possess magnetic fields can be tested. Searches should be undertaken for coherent pulses in the vicinity of the calculated spin frequencies of Table 1. Unusual GBHC burst events should be examined for burst oscillations. It might also be possible to find cyclotron resonance features in the range 0.01 - 1 keV in the spectra of the GBHC. Dynamic mass determinations for Cir X-1 and XTE J1550-564 are definitely needed. The properties of XTE J1550-564 and Cir X-1, including their high frequency QPOs, are strikingly similar. It is highly unlikely that Cir X-1 possesses a strong magnetic field while XTE J1550-564 does not. If XTE J1550-564 possesses a similar magnetic field, it should display a ‘Z’ track in a color-color diagram similar to that of Cir X-1. The onset of ‘kHz’ QPO at frequencies typically within $\sim 50\%$ of the spin frequency would seem to confirm the spins found here for Cir X-1 and XTE J1550-564.

5. CONCLUSIONS

We have shown that the luminosities of the spectral state switches of NS in LMXB can be used to accurately predict luminosities that are $\sim 10^{3-4}$ fainter at the light cylinder and in quiescence. Spin rates and magnetic moments that we have found for NS are comparable to those found for known millisecond pulsars. The magnetospheric model on which these calculations rely depends strongly ($\mu^2\nu^4$) on magnetic moment and spin of the NS and is therefore incompatible with ADAF models. This significantly sharpens the question of how GBHC produce their quiescent spectra. We have shown that their quiescent luminosities can be accurately calculated for the magnetospheric model from spectral state switch luminosities that are $\sim 10^4$ brighter. In the process, we have found a reasonably consistent set of GBHC magnetic moments and spins for eight GBHC and Cir X-1. We acknowledge that the parameters, K , η and R_6 are poorly constrained, but the values used here certainly seem plausible. Both η and R_6 are expected to be mass dependent quantities.

The soft spectral state in this model arises from the surface of the central object. This requires a paradigm shift away from supposing that all soft spectral components arise in the disk. We attribute the ‘ultrasoft’ radiations of GBHC to greater surface redshifts. It is well known that power law emissions and hard spectra are generated by accreting pulsars but there is no agreement on how they do it. Magnetohydrodynamic simulations of the propeller regime have not yet provided the details.

We have included predictions and suggested tests of our model. We expect that all GBHC and NS properties can eventually be understood in terms of a unified magnetospheric model. If it can be conclusively shown that GBHC have magnetic moments, then some way will need to be found, within the framework of General Relativity to prevent the physical realization of the event horizon. It is the horizon that disconnects external magnetic fields from generator currents in the interior. The changes of theoretical interpretation necessary to eliminate physical occurrences of the horizon might very well leave the landscape of compact objects, frame dragging, marginally stable orbits and curved spacetime little changed.

We thank Rudy Wijnands for pointing out significant errors in an earlier draft. We are indebted to John Tom-sick for sharing information prior to its publication and we thank Jeroen Homan for useful information.

APPENDIX

Appendix

OBSERVATIONAL DATA

Aql X-1: Campana et al. (1998) reported spectral hardening beginning at $L_{min} = 1.2 \times 10^{36}$ erg/s, $L_c = 4 \times 10^{35}$ erg/s and complete cessation of the rapid decline at about 1.2×10^{33} erg/s, which we identify as $L_{q,max}$.

4U1608-52: Spectral hardening began in decline at $L_{min} = 10^{37}$ erg/s (Mitsuda et al. 1989). We take $L_c = 2.9 \times 10^{36}$ for the March 1990 hard spectral state (Yoshida et al. 1993). Garcia et al. (2001) have reported a quiescent luminosity of $L_q = 2 \times 10^{33}$ erg/s.

Sax J1808.4-3658 reached a luminosity level of $\sim 2.5 \times 10^{36}$ erg/s, ($d = 2.5$ kpc) declined slowly to about 8×10^{35} erg/s and then began a rapid decline. (Gilfanov et al. 1998, Heindl & Smith 1998). Very similar decline characteristics were shown for *Aql X-1*, for which we identified the luminosity at the start of rapid decline and spectral hardening as L_{min} . *Sax J1808.4-3658* never displayed a soft spectral component. It is conceivable that it never reached L_c , but if so then the 401 Hz pulses would have to have originated in interaction between the magnetic field and disk rather than on

polar caps. We think it more likely that L_c was exceeded as surface bursts have been observed for it. A recent analysis of its 1996 outburst (in't Zand et al. 2001) has also confirmed that burst oscillations occur at the 401 Hz spin frequency. By analogy with the light curve of Aql X-1, we take $L_{min} \approx 8 \times 10^{35}$ erg/s ($d=2.5$ kpc), as the luminosity at the start of rapid decline. With this choice, we obtain $\mu_{27} = 0.53$ and calculate a quiescent luminosity of 10^{32} erg/s, in reasonable agreement with observation. We also calculate $L_c = 1.9 \times 10^{35}$ erg/s (for $d = 2.5$ kpc). There may be a change of trend of the decline at this luminosity similar to that of Aql X-1, however there is only one luminosity data point to suggest this. But there is also a change of trend of pulse amplitude fraction at this level. Pulsations continued to be observed during the entire decline phase (Cui, Morgan & Titarchuk 1998) and well below the luminosity that we calculate as L_c . These observations may be consistent with having a magnetic axis with significant inclination relative to the rotation axis. Whatever the case, it should be clear that Sax J1808.4-3658 is a pulsar of known spin. Therefore we use Equation 1 to determine its magnetic moment, we obtain $\mu_{27} = 0.44 - 0.62$ ($d = 2.5$ kpc). Equation 6 then yields $L_{min} = 0.55 - 1.1 \times 10^{36}$ erg/s compared to $\sim 8 \times 10^{35}$ erg/s at the start of its rapid decline. Although our identifications of L_{min} and L_c appear to be consistent with the observed spin and quiescent luminosity, we reiterate that these identifications are based only upon the analogy with Aql X-1. Sax J1808.4-3658 did not show a soft spectrum. If we are correct that it exceeded L_{min} without producing a soft spectrum, then we would not expect it to ever become soft if observed at higher luminosities in subsequent outbursts.

Cen X-4: For Cen X-4, the values of L_{min} and L_c shown in Table 1 were estimated from the start of rapid decline on May 23, 1979 and the arrest of decline of the light curve on May 28, 1979 (Kaluzienski, Holt & Swank 1980).

4U 1916-053: Boirin et al. (2000) report $L_c = 3.2 \times 10^{36}$ erg/s and a soft state luminosity of $L_{min} = 1.4 \times 10^{37}$ erg/s. The 370 Hz spin calculated for it is an upper limit, as it is not certain that spectral softening was complete.

4U 1730-335: Campana et al. (1998) report $L_c = 10^{37}$ erg/s at the start of spectral hardening. Fox et al. (2000) have found a burst oscillation frequency of 307 Hz.

KS 1731-26: We take the reported hard state luminosity (Sunyaev 1990) to be $L_c = 1.8 \times 10^{36}$ erg/s.

Cir X-1: Neither spin rate nor mass are available for the enigmatic Cir X-1. $L_{min} = 6.3 \times 10^{38}$ erg/s and $L_c = 3 \times 10^{37}$ erg/s can be determined from observations just before and two hours after a spectral hardening transition on Sept 20-21, 1977 (Dower, Bradt & E Morgan 1982).

GRS 1124-68: Misra & Melia (1997) showed that its inner disk radius increased to about $27R_s$ (here $R_s = 2GM/c^2$, 400 km for $5 M_\odot$) after the spectral state transition. Ebisawa, et al (1994) give a luminosity of $L_c = 6.6 \times 10^{36}$ erg/s for the low state for the period June 13 - July 23, 1991. $L_{min} = 2.4 \times 10^{38}$ erg/s is the average of the period March 10 - April 2, 1991. The assumption of $r_c = 400$ km yields $\nu_s = 16$ Hz.

GS 2023 + 338 never displayed an ultrasoft spectral component, but on May 30, 1989 it changed luminosity by a factor of 21 in 10 s, from 10^{39} erg/s to 4.8×10^{37} erg/s (Tanaka & Lewin 1995). When the luminosity diminished, the reduction in the 1 - 10 keV band was greater than for higher energies, which hints of a weak spectral state transition. Thus we take these luminosities to be L_{min} and L_c , respectively. From spectral analysis Życki, Done and Smith (1997b) found $r_{in} = 25R_G$ (here $R_G = GM/c^2$, 263 km for $7M_\odot$) and $35R_G$ (368 km), respectively, for June 20, 1989 and July 19-20, 1989. Luminosities (0.1 - 300 keV) for these dates based on spectra of Tanaka (1992) are 1.9×10^{37} erg/s and 6.3×10^{36} erg/s, respectively. The radii scaled as $L^{-2/9}$ yield values of the co-rotation radius of 214 km and 234 km. We take the mean of 224 km as the co-rotation radius and find $\nu = 46$ Hz. Quiescent luminosities of 6.9×10^{33} erg/s (Chen, Shrader & Livio 1997), 8×10^{33} erg/s (Tanaka & Shibazaki 1996), and 1.6×10^{33} erg/s (Garcia et al. 1997) have been reported.

XTE J1550-564—Spectral data reported (Sobczak et al. 2000) for this GBHC showed rapid decrease of luminosity from $L_{min} = 2 \times 10^{38}$ erg/s ($d = 6$ kpc) and large changes of spectral hardness on Oct. 24, 1998 and again on Mar. 12, 1999. A lower average luminosity level of $L_c = 9.2 \times 10^{36}$ erg/s was reached for the period April 15 - 25, 1999. High frequency QPO's of 285 Hz have been reported for XTE J1550-564 (Homan et al. 2000). Assuming these to originate with the accretion disk radius near the marginally stable orbit, a mass of $\sim 7M_\odot$ is implied. Wilson & Done (2001) have found an inner disk radius of $22GM/c^2$ (228 km for $7 M_\odot$), from which we obtain a spin of 45 Hz. The inner disk radius for disk blackbody spectral fits (Sobczak et al. 2000) also show a dramatic increase for the April 15 - 25 period in accord with our identification of L_c . Quiescent luminosity of 7×10^{32} erg/s (0.5 - 7 keV, $d = 4$ kpc) has been reported by Tomsick & Kaaret (2001), however this was soon after the outburst ended.

GRO J1655-40: L_{min} was reached at 3.1×10^{37} erg/s approximately July 29, 1996 (Mendez, Belloni and van der Klis 1998, Fig. 1). The rapid decline was arrested at about 10^{36} erg/s, which can be taken to be L_c .

A0620 00: Spectral hardening began about 100 days after the start of the 1975 outburst and continued until interrupted by a reflare. At the start of spectral hardening we find $L_{min} = 4.5 \times 10^{36}$ erg/s (Kuulkers 1998, see Figs 1 & 2). At the start of the reflare we find $L_c \approx 1.4 \times 10^{35}$ erg/s, though it is not clear that spectral hardening was complete.

Cygnus X-1 exhibits spectral state switches with very little change of bolometric luminosity at about $L_c = 3 \times 10^{37}$ erg/s. Done & Życki (1999) find an average inner disk radius of $27GM/c^2$ (400 km for $10 M_\odot$) that changes very little as the spectrum pivots. We find a corresponding spin frequency of 23 Hz.

GRS 1915 + 105 displays oscillations with peaks above the Eddington limit followed by hard states that are lower in luminosity by a factor of 3 - 6. Belloni et al. (1997) have attributed the intervals between flares to the time required for the inner disk to refill on a viscous time scale, which is likely correct. Disk blackbody spectral fits (Belloni et al. 1997) show that r_{in} oscillates between about 20 km and 80 km, but occasionally reaches only 55 km, followed immediately by another burst. 55 km would be the innermost marginally stable orbit radius for $7M_\odot$, which is therefore adopted as the

mass. A 67 Hz QPO has been observed (Remillard et al. 1997, Remillard & Morgan 1998) that is sharp ($Q > 20$) and stable for factors of 5 luminosity change over six months time. If this is the spin frequency, a co-rotation radius of 174 km is implied. The low state between flares reached about 4×10^{38} erg/s for a radius of about 80 km. Scaling the luminosity ($\propto r^{-9/2}$) for 174 km, we find $L_c = 1.2 \times 10^{37}$ erg/s, $\mu_{27} = 128$ and we predict $L_{min} = 1.6 \times 10^{38}$ erg/s.

GS 2000 + 25: Życki, Done and Smith (1997a) have found a spectral state switch for GS 2000 + 25. When a strong soft component is present the disk is highly ionized and iron fluorescence strongly relativistically smeared. The disappearance of the soft component is accompanied by hardening of the power-law and a decrease of ionization. Little change of inner disk radius occurs at the transition, but the subsequent decline of luminosity is accompanied by an increase of inner disk radius. We identify $L_c = 1.5 \times 10^{35}$ erg/s for the hard state of Dec. 16, 1989. If we use an inner radius of (50 - 100) R_g (500 - 1000 km with $R_g = GM/c^2$) as the co-rotation radius (Done, C. personal communication) we obtain $\nu_S = 14$ Hz for the smaller radius.

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